

ENGINE "ON CONDITION" MONITORING - CF6 FAMILY

60's THRU THE 80's

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SUMMARY

The "On Condition" program which was introduced in the late 60's was immediately accepted by the industry. This program which provided the foundation for timely and economical maintenance procedures in fault detection and isolation has resulted in a significant reduction in material and labor cost. The in-flight shutdown rates (IFSD), the unscheduled engine removal rates (UER) and the departure reliability reported show that the airlines' "On Condition" monitoring programs are very effective in reaching a high level of reliability. In the near future, with the added emphasis on fuel conservation/economics and in conjunction with the advancements and refinements in electronics, it is anticipated that the on-board Engine Condition Monitoring Systems will become economically feasible through the expanded effectiveness in performance monitoring of the basic modules of the engine and the integration with the overall engine workscope. The CF6 Condition Monitoring experience beginning in the late 60's up through the future expectations of the 80's, is discussed in this paper.

INTRODUCTION

Monitoring of the overall engine condition has proved to be an effective maintenance tool both at the line station, as well as at the home base by the early detection of engine faults, erroneous instrumentation signals and by verification of engine health. It currently encompasses all known methods from the manual procedures to the fully automated Airborne Integrated Data Systems (AIDS). Future programs (Figure 1) will be built around the proven capabilities of today's systems, the continual growth in maintenance capability and effectiveness through improved data acquisition/analysis, and the projected module performance analysis program under development. Cost effectiveness, unquestionably, remains the prime criterion to an airline in the selection/definition of its monitoring system. Today's increased need for fuel conservation and to control the operating expense, coupled with recent advancements in the capabilities of on-board electronic equipment, has stimulated interest in the potential of the Expanded AIDS systems and, accordingly, the monitoring system architecture for future aircraft and engines.

Equally important in the establishment of future programs is the stressed need and acceptance of the team concept, a concentrated effort by members from the manufacturers of aircraft, engine, and AIDS equipment and the airlines. To date, the A310/CF6-80 AIDS team organized around the future application has proved to be most effective and is heartedly endorsed by the participants.

METHODS/SYSTEMS

The methods/systems (see Figure 2) utilized today and expected to be carried on into the future encompass the complete spectrum from fully manual (using only cockpit instrumentation) to completely automated with expanded instrumentation and data acquisition. The end objective of all of these methods/systems is, however, the same, and that is to afford the maintenance person the means to establish the required corrective action in a timely fashion.

Although the practices vary from airline to airline, the basic procedure is to routinely monitor the corrected trend data and the relative nominal data for variations. Whenever a shift is observed, the maintenance center analyzes the variation for validity, compares it to past experience and, thereby, establishes a level of severity, and then requests specific inspections and additional data signatures. These results are then compared with historical data and the maintenance manual to establish the corrective action. These tools (see Figure 3) have been proven and are being effectively utilized by airline maintenance today.

The integration of trend plots with non-destructive inspection results, together with the engine historical record, and with proven diagnostics affords maintenance the very means necessary to make effective decisions. It is recognized that individually, the separate techniques are somewhat inadequate, the secrets lie in the effective combination where they complement and support each other.

The parameters which are measured today on CF6 engines are shown in Figure 4. These parameters provide the basic information for trending an engine against itself for both short- and long-term diagnostics, the fuel consumption, mechanical integrity and the refined life cycle count programs. Initial effort toward Modular Performance Analysis has also begun with these same parameters. Additional parameters such as low pressure turbine discharge pressure and temperature are under study.

TREND PLOTS/EXPERIENCE

Manual

Manual trend plots are generated from data recorded from the cockpit instruments either on-board the aircraft by a member of the flight crew or on-ground by a maintenance person. Typical examples of manual trend plots are shown in Figure 5. These particular plots show the shift in engine parameters due to excessive bleed flow. Note the relative characteristics between the parameters differ substantially based on whether the bleed is recouped within the engine or dumped overboard. The excessive bleed from the manifold leak was dumped overboard. In this case, the trend plot shows increases in the exhaust gas temperature (EGT), fuel flow (FF), core speed (N_2) and a decrease in engine pressure ratio (EPR). A faulty HPT second stage seal is an example of an internal leak, that is, the air returns to the primary stream downstream of the high pressure turbine first and second stage nozzles, respectively. In this case, the on-board manual trend plots showed a significant increase in EGT over a short period of time without any apparent change in the level of core speed, fuel flow, engine pressure ratio and vibration. At first glance one would suspect faulty instrumentation; however, inspection of the high pressure turbine stator with a flexible borescope located the faulty seal and provided the basic information for the decision to remove the engine, replace the seal, rebuild the engine with original modules and place it on site as a ready spare.

Semi-Automatic

The semi-automatic method which is known in the industry as ADEPT, CEML, FML, TEMP, etc., provides computer printouts consisting of tabulations and trend plots. The input which is the same as that for the manual method consists of the engine parameters and flight conditions recorded from the cockpit instruments during steady-state cruise. The data is normally taken at least once during each flight, forwarded to the home base for processing through the on-ground computer. The output consisting of the tabulation of the flight conditions, engine parameters along with bleed conditions and the trend plots versus flights of vibration (V), exhaust gas temperature (G), fuel flow (F), core speed (2), etc., are reviewed daily by the maintenance person. In the future, it is anticipated that the input into the ground based computer will be automatic from magnetic tape recorded on-board the aircraft or by radio communication link.

Examples of the semi-automatic trending as obtained from a ground-based computer using the manually recorded data from cockpit instruments (see Figure 6) show typical changes due to instrumentation faults, compressor foreign object damage, and an on-wing fan trim balance. As shown, the shifts in the body of the trend plots appear to be gradual while in reality they are step changes. The reason for the gradual change is that the data versus flights is smoothed by averaging over several readings thereby damping a step change. The magnitude of the step change is reflected by the raw data which is shown at the bottom of the trend plot.

AIDS

AIDS is a fully automated system utilizing the output from the on-board printer and/or recorder as a direct input into the on-ground computer. As the computer is quite flexible, the output can be readily customized to satisfy the particular situation including transient as well as steady-state conditions.

Relative to manual methods, AIDS provides advantages in availability of data sequences during transients, recording additional parameters, greater accuracy and repeatability through established stability criteria. Some typical examples are shown in Figure 7. As seen, the high transient characteristics of the parameters during takeoff can be recorded and printed out in a comparison versus time. This is a most valuable tool in assessing variations in pressures, temperatures and rpm over short time intervals. Also shown, is the versatility in formatting the trend plots in reverse chronological order against the latest, intermediate and the very early flights and, of course, the PLOT/LIST which tabulates the data versus time.

SOAP

Although some operators effectively monitor the lube system by checking only the screens and filters, others have found SOAP (Spectrographic Oil Analysis Program) to be a useful tool in monitoring specific wear problems, such as the number three bearing inner race hub wear (see Figure 8). It is to be recognized that the effective utilization of SOAP requires strict discipline in monitoring the lube system. As shown, any changes to the system, such as adding or draining oil, will completely distort the trend plot. Likewise, any contamination within the sampling and analytical equipment will distort the trend plot. And, of course, the sampling must be accomplished on a scheduled time interval.

Borescope and Radiograph

An area, in which great strides have been made and of which the industry can be very proud is that of borescope and radiographic non-destructive testing equipment and techniques. Equipment and techniques available today, not only afford the means to inspect deep within an engine, but also provide the means to readily visualize the actual condition. Figure 9 shows typical examples of the visibility these techniques provide and a measure of their value to the maintenance task. Many will undoubtedly remember when the borescope was hot enough to burn your hand and the visibility was completely inadequate.

Diagnostics

Not to be forgotten and, obviously, the most valuable link in this maintenance chain of events is the diagnostics/decision by the maintenance person or persons. One of the most valuable lessons learned is that the most

exotic tools and methods are most ineffective without dedicated people. Humorously, but also quite seriously, Figure 10 tries to emphasize this point. Our message, people and their vital communication links between the line station and main base, are the key.

MEASUREMENTS

So how is the industry meeting the challenge. The trends (see Figure 11) on dispatch reliability, in-flight shutdowns, and shop visit rate for the CF6-50 clearly show that they are doing very well and improving with time. These measurements also show that the industries' dedication to the "on condition" concept is fulfilling its objectives.

FUTURE

Now, let us as a member of the industry look at the future. In the late 70's, the airlines jointly provided specifications covering their future needs for monitoring engine health. These specifications can be summarized into the five basic programs (see Figure 1). The overall objective of these programs is to provide an improved engineering/maintenance tool. As noted earlier, the trending and mechanical integrity programs have been proven and are essentially in place while the others are in various stages of development. Several of the airlines are confident that with the team concept that the Expanded AIDS will be a most effective tool. One of these operators is Lufthansa German Airlines who, as a member of the ATLAS Group and an operator of CF6-powered aircraft, today monitor engines by the semi-automatic method. In the 80's, they will be operating the CF6-powered A310 with an Expanded AIDS and plan to utilize it to the fullest.

Rational for DLH Expanded Aids/A310

Major elements in Lufthansa's decision to incorporate an Expanded AIDS were the emphasis on the need for pre-shop identification of faulty engine modules, for efficient corrective shop action and for engine operation at minimum operating cost by making optimal usage of fuel and engine parts/materials.

A simplified model (Figure 12) shows how fuel burn cost per engine flight hour - caused by performance deterioration of a high spool module - increases and how the module restoration cost per hour decreases versus the flight cycles accumulated at time of restoration.

The summation of these two curves provides the accumulated module cost versus flight cycles with the minimum indicating the performance life of the module under consideration.

Superimposing appropriate curves of all the modules leads to the optimum point in time that the engine should be removed for restoration of the degraded module's performance.

Figure 13 shows the effect of increasing fuel cost on the minimum cost/performance life curve. The assumed fuel cost rise over the years to come will significantly reduce the usable performance life and also drastically steepen the overall cost curve which implies increasing losses in case of delayed performance restoration.

In view of the fact that the deterioration characteristics vary significantly from module to module of the same type, a typical cycle dependent deterioration rate cannot be assumed for identifying and scheduling the optimum restoration time. Hence, individual engine module performance analysis and monitoring is imperative.

The realization of such a concept centers around the additional instrumentation, an Expanded AIDS and the necessary ground based computer system with an effective analysis algorithm which is now under development by the engine manufacturer.

AIDS Configuration

The architecture (see Figure 14) of Lufthansa's A310 AIDS is built around an "On-Board" digital system incorporating an analog-to-digital multiplexer (PMUX), ARINC 429 data bus, Data Management Unit (DMU), Digital Flight Data Acquisition Unit (DFDAU), the Digital Flight Data Recorder (DFDR), a Control Display Unit (CDU), a printer and Quick Access Recorder (QAR). The output from the "on-board" printer and recorder will be input into the ground facility for further computation and documentation.

EXPECTATION

Now let us project the future potential from an industry standpoint (see Figure 15). The potential is great for further expansion and improvement of today's engineering/maintenance tools. The means and methods by which this will be achieved will certainly vary from operator to operator. A key approach is to build on proven experience and to extend the programs by: utilizing the increased memory/buffer size, increased sampling rates, improved stability criteria, optimizing the Modular Performance Analysis/Work Scope, improving diagnostics through effective means to detect stalls, isolating hot starts, establishing levels of EGT margin, incorporating/expanding divergence monitoring, enhancing short term monitoring through on-board exceedances/trends flags, and automatically documenting levels of reduced power.

In retrospect, "On-Condition" maintenance concept of the 60's and 70's have provided a sound foundation for an effective maintenance tool for the airline industry. While there is great promise and high potential for

further expansion and improvement of the maintenance capability, any improvements and expansions must be economical and practical to become acceptable. The development and implementation of a cost effective engine diagnostic system will be the challenge of the 80's.

Engine Condition Monitoring

- **Programs Today/Future**
 - **Trending**
 - **Module Performance Analysis**
 - **Fuel Consumption Survey**
 - **Mechanical Integrity**
 - **Refined Life Cycle Counting**

FIGURE 1

Trending Methods/Systems

- **Manual On-Board**
- **Manual On-Ground**
- **Semi-Manual (Computer)**
- **Aids (Airborne Integrated Data Systems)**

FIGURE 2

Tools

- Trend Plots
 - Gas Path
 - Mechanical
 - Soap (Spectrographic Oil Analysis Program)
- Borescope Inspection
- Radiographic Inspection
- Diagnostics
 - Fault Detection/Isolation

FIGURE 3

Condition Monitoring Sensors

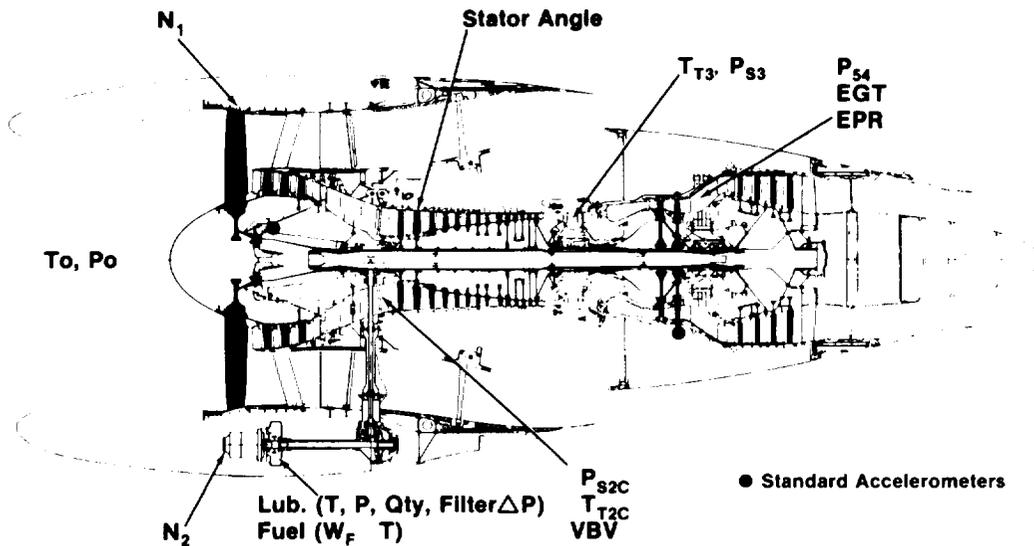


FIGURE 4

Trend Plots/Experience

- Manual
 - Typical Trend of Excess Bleed
 - On-Board Real Time Trend Plot
 - HPT Second Stage Seal

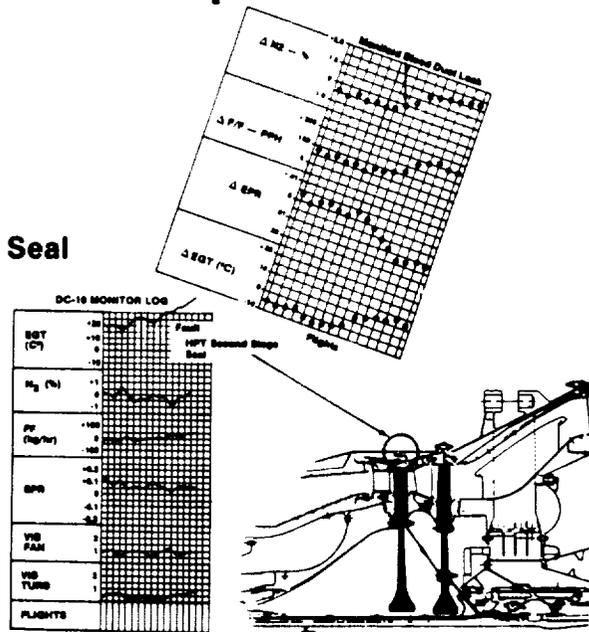


FIGURE 5

Trend Plots/Experience/Diagnostics

- Semi Automatic

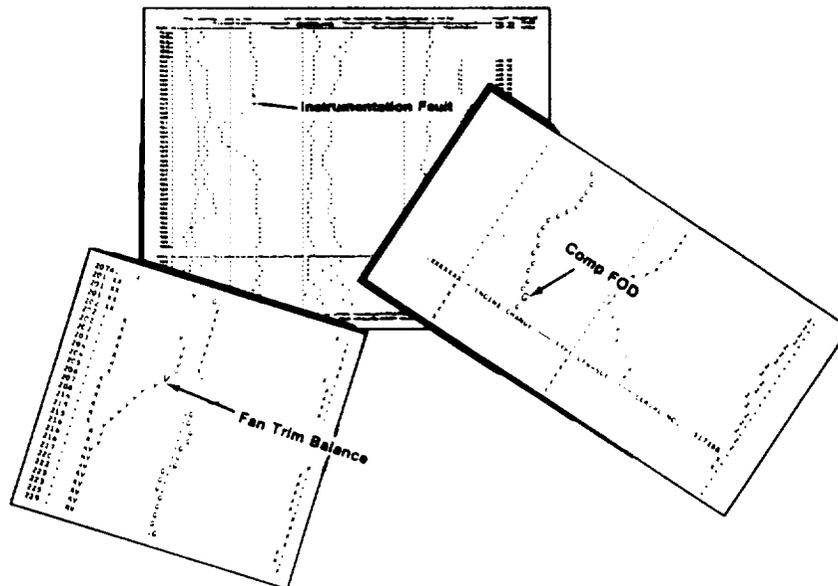


FIGURE 6

Trend Plots/Experience

- Aids

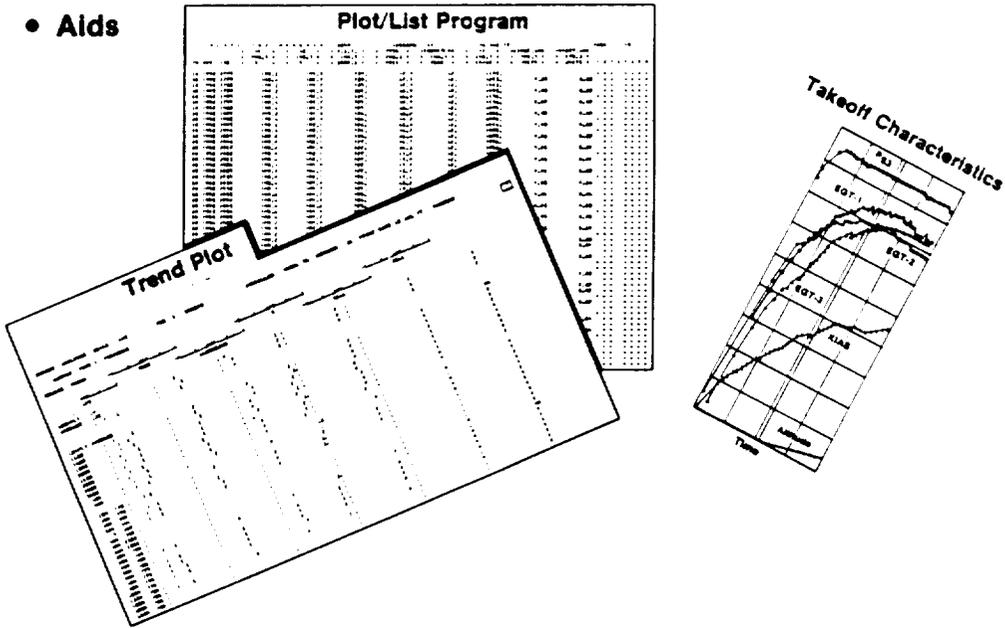


FIGURE 7

Trend Plot/Experience/Diagnostics

- SOAP

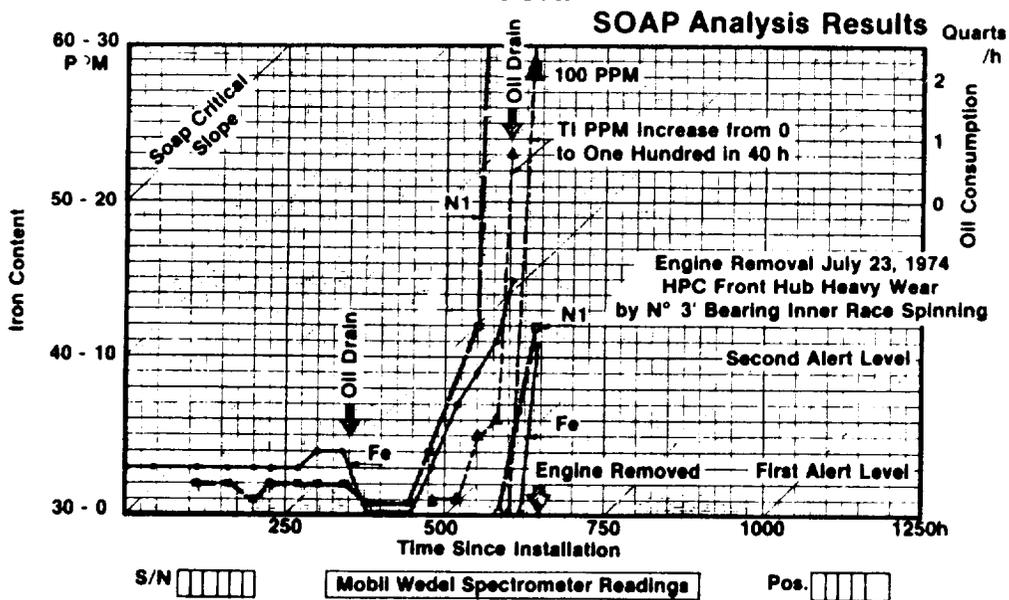


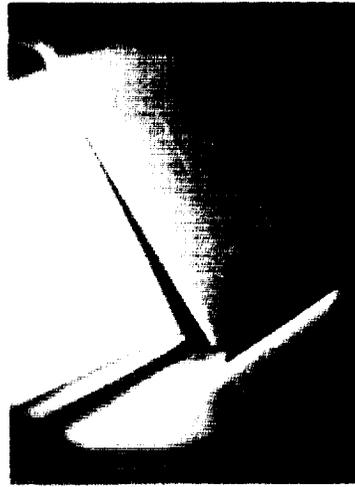
FIGURE 8

Borescope/Radiography

Borescope Viewing Detail



Fuel Nozzle



HP Compressor Blade

Radiographic Shot



FIGURE 9

Diagnostics

- Key

Personnel

Understanding/Experience
Engines and Systems

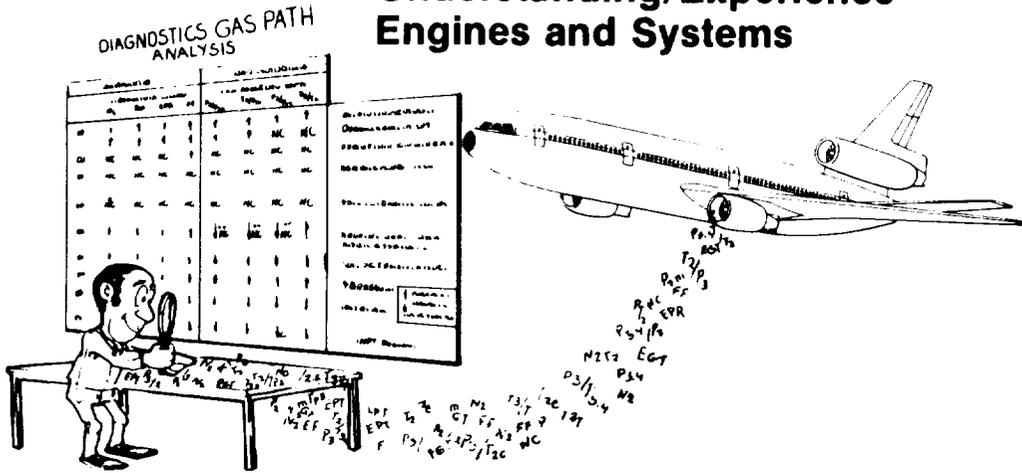


FIGURE 10

CF6-50 Engine Reliability

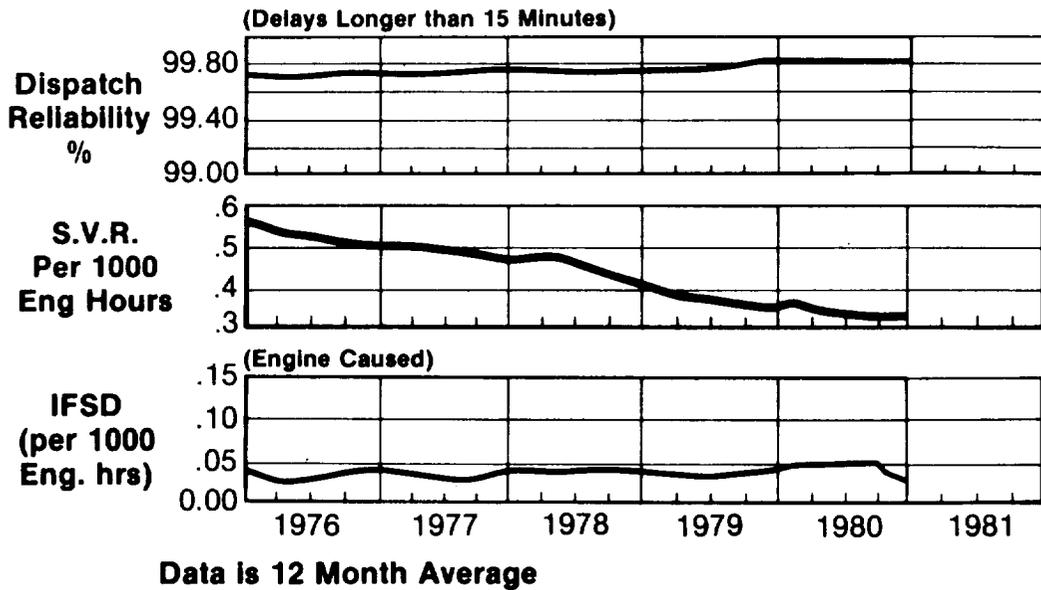


FIGURE 11

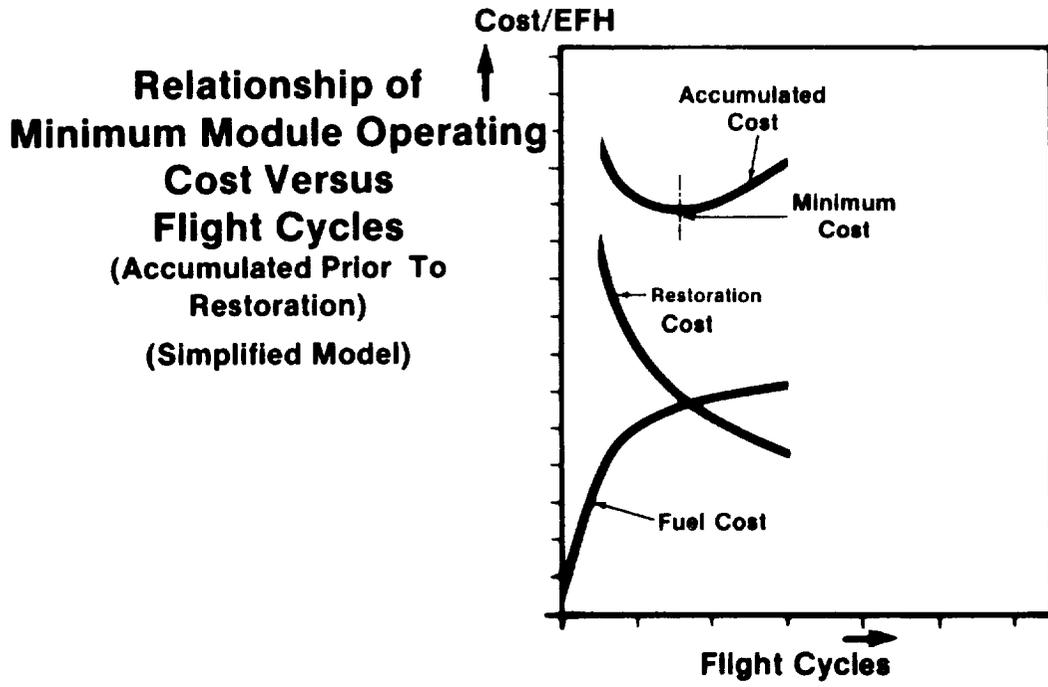


FIGURE 12

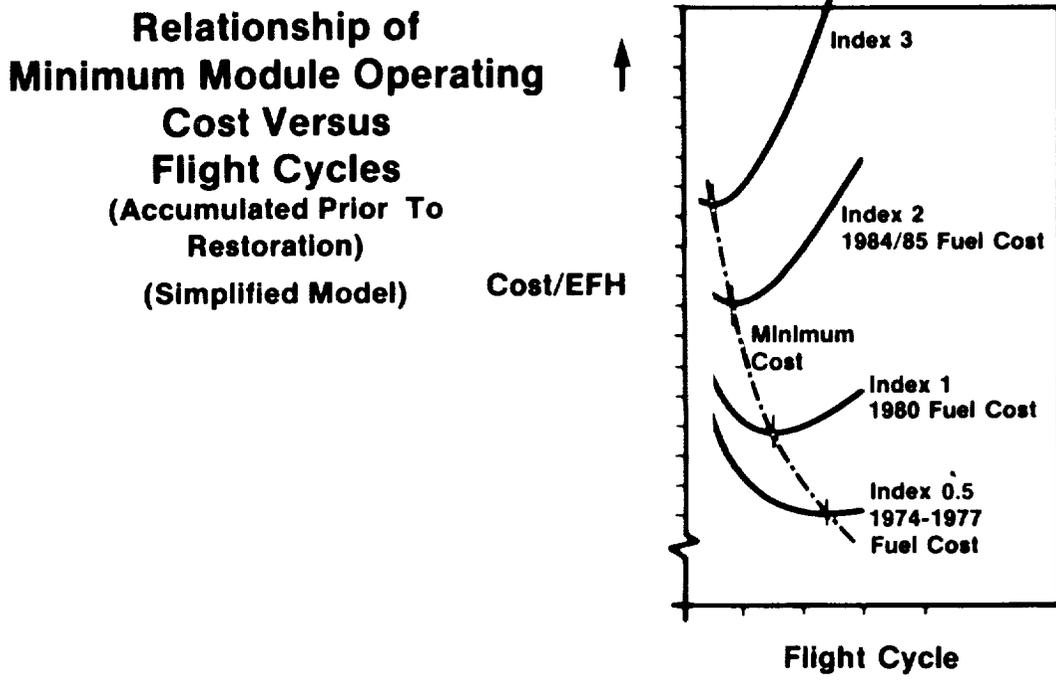


FIGURE 13

Lufthansa A310 Aircraft Integrated Data System

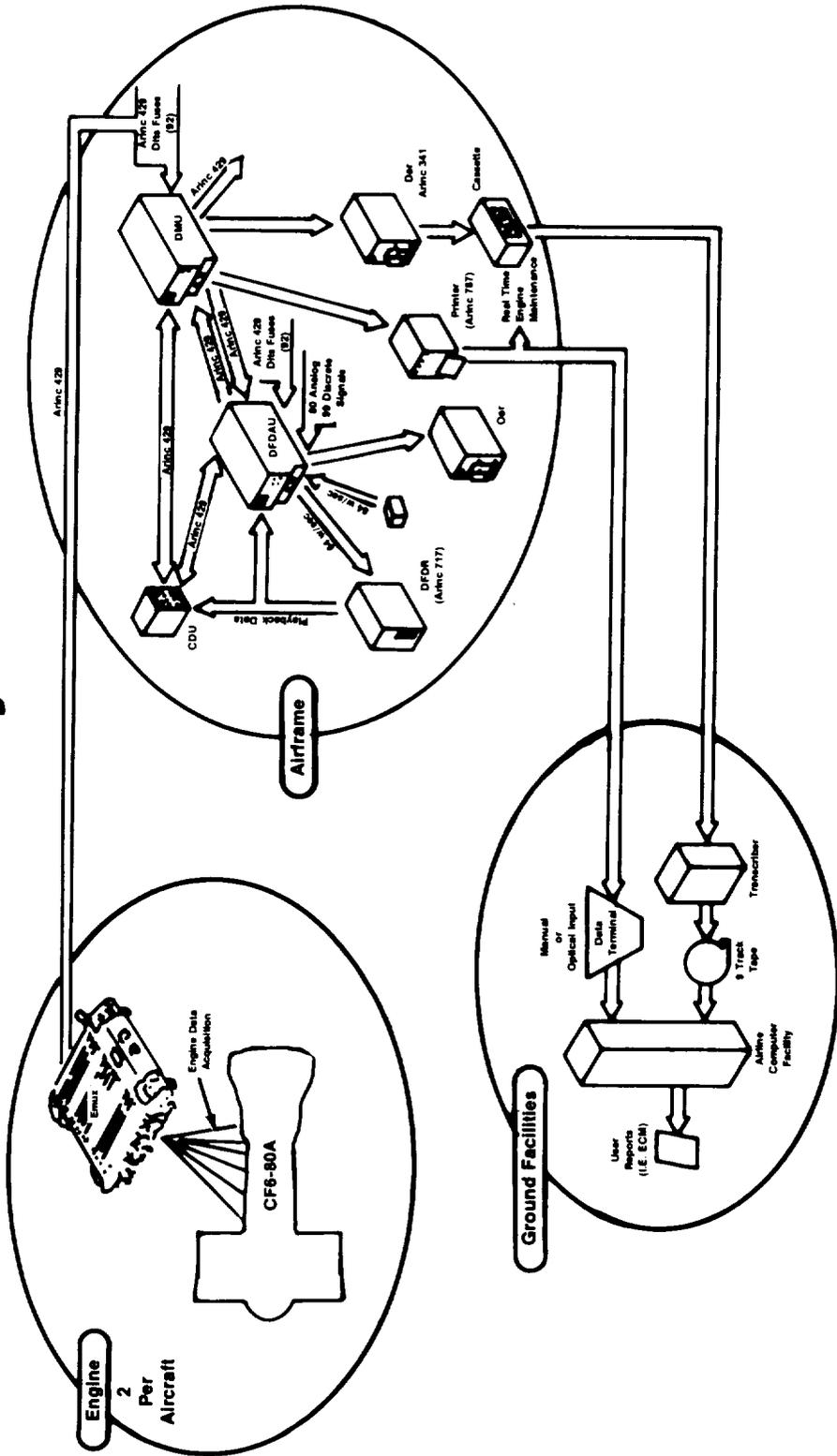


FIGURE 14

Future

Objective

- **Expand on Effectiveness of Maintenance Tool**

Approach

- **Build on Proven CF6 Experience**
- **Extend Programs**
 - **Modular Performance Analysis**
 - **Improved Diagnostics**
 - Stall Detection**
 - Hot Starts**
 - EGT Margin**
 - Divergence Monitoring**
 - On-Board Trends**
 - **Benefits of Reduced Power**

FIGURE 15